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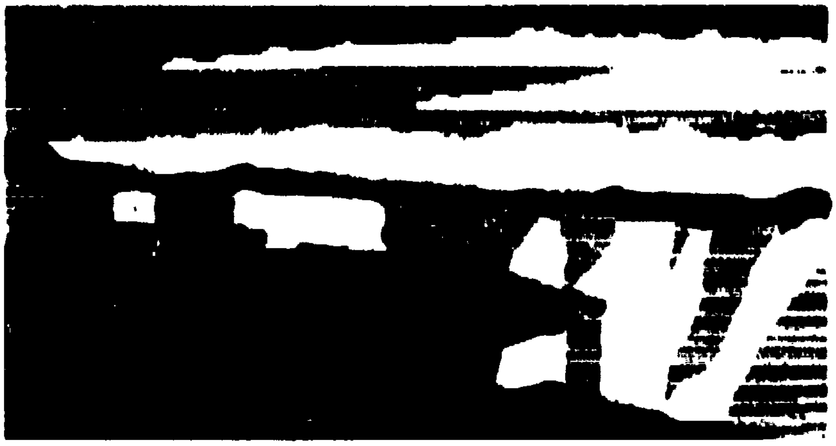

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QCD SUM RULES AND PROPERTIES OF BARYONS IN NUCLEI

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The use of medium-energy experiments to constrain in-medium four-quark condensates, whose uncertainty is currently the most important problem inhibiting the use of QCD sum rules to study hadrons in nuclear matter, is discussed. A value for a particular linear combination of these condensates is extracted using results of an Isobar-Doorway model analysis of pion-nucleus scattering data and a QCD sum rule analysis of the mass of the $\Delta(1232)$ in nuclei. Extending the analysis to include higher-lying baryon resonances is possible with data from modern facilities.

A promising development for nuclear physics has arisen from the observation that the low Q^2 properties of isolated hadrons (e.g., their masses and couplings to other hadrons) are quantitatively related to the dynamics of high-Q^2, where nonperturbative behavior is described by condensates of quarks and gluons[1] using the method of QCD sum rules. A question of interest now is whether the sum rule method is a viable approach for understanding nuclear phenomena in QCD. The answer appears to be "yes," but the quark and gluon structure in the nucleus remains to be fully characterized. This requires theoretical and experimental studies as discussed below.

In the extension to nuclei,[2] the condensates become matrix elements of quark and gluon fields in the nuclear ground state, or nuclear vacuum $|A\rangle$. They are more numerous for a variety of reasons. One is that there is now a new four-vector characterizing the system, namely the four velocity of the nucleus u^μ, giving a richer possible tensorial structure. Another is that the condensates develop a density dependence. The four-quark condensate is an especially important consideration in nuclei. Up to now, this condensate, $\langle A|\bar{q}q\bar{q}q|A\rangle$, has been treated by factorization, and the results for the scalar mass of a nucleon in a nucleus depend on how density dependence is assigned in the four-quark condensate after factorization.[3] One concludes from this that factorization is not justified, and that to apply QCD to nuclei the four-quark vacuum structure of nuclei must be fixed from other sources.

To go beyond the factorized approximation in the QCD sum rule analysis of hadrons in nuclei, it is necessary to determine the four-quark condensates

$$c_i = \langle A|\bar{q}\Gamma_i q\bar{q}\Gamma_i q|A\rangle \; . \tag{1}$$

where Γ_i corresponds to the eight spin structures $\Gamma_i = 1;\ \hat{u};\ \gamma_5;\ \gamma_5\hat{u};\ \gamma^\mu;\ \gamma_5\gamma^\mu;\ \sigma^{\mu\nu}$; and $\sigma^{\mu\nu}u_\nu$ (labeled $i = 1; 4; 5; 6; 9; 10, 11$; and 12 in the following text), with $\hat{p} = \gamma^\mu p_\mu$. One can either use experimental information to determine these condensates,[4] as we next discuss, or one may use models, e.g., Ref. 5.

We have proposed determining the in-medium four-quark condensates by using the known properties of the $\Delta(1232)$ resonance in nuclei.[4] To do this, one may take advantage of one of the important discoveries with meson facilities, namely that it is possible to extract the propagator of a $\Delta(1232)$ from the analysis of pion-nucleus scattering.[6–8] One may do this using the phenomenological isobar doorway model[6,7] analysis, which determined that the Δ mass in the nuclear medium is within about 10 MeV of the free Δ mass and that its width is broadened by about 10%.

The starting point of the QCD sum-rule analysis of the $\Delta(1232)$ in nuclear matter is the two-point function, usually called the correlator:

$$\Pi(p)^{\Delta^*}_{\mu\nu} = i\int \left\langle A \middle| T\left[\eta^{\Delta}_{\mu}(x)\bar{\eta}^{\Delta}_{\nu}(0)\right] \middle| A \right\rangle d^4x e^{ix\cdot p} \ , \tag{2}$$

where the quantity $\eta^{\Delta}_{\mu}(x)$ is a composite field operator, the $\Delta(x)$ current,

$$\begin{aligned} \eta^{\Delta}_{\mu}(x) &= \varepsilon^{abc}\left[u^a(x)^T C\gamma^{\mu} u^b(x)\right] u^c(x) \ , \\ \left\langle 0 \middle| \eta^{\Delta}_{\mu}(x) \middle| \Delta \right\rangle &= \lambda^*_{\Delta} v_{\mu} \ , \end{aligned} \tag{3}$$

where C is the charge conjugation operator and the $u(x)$ are u-quark fields labeled by color, λ^*_{Δ} is a structure parameter and v_{μ} is a Raritu-Schwinger (spin 3/2) spinor.

In general terms, the procedure follows that in free space.[4,9] The RHS is the same as before, except that for the Δ mass we take

$$M_{\Delta^*} = M_{\Delta} + \delta M^s_{\Delta} + \delta M^u_{\Delta}\hat{u} \ , \tag{4}$$

and require a modified value of the structure parameter λ^*_{Δ}. We choose three standard Lorentz structures to determine λ^*_{Δ}, M^*_{Δ}, and δM^u_{Δ}. On the left-hand side we, of course, have to use the in-medium values of the condensates. This includes the non-factorized four-quark condensates. With our choice of sum rules, the four-quark contribution vanishes for all except Π_p, and thus the data determines the following linear combination of the c_i's,

$$\Pi^{4q}_p = \frac{1}{2p^2}\left[c_1 - c_3 - 2c_4/9 + 2c_6/3 + c_9/9 - c_{10}/3 + 4c_{11}/9 - 16c_{12}/9\right] . \tag{5}$$

Our results are as follows. (1) Using the result that the pole position is approximately the same as its free value, which we take as $M^*_{\Delta} = 1.35$ GeV, we find that the shift from the factorized value is $\delta\Pi^{4q}_p = -0.026$ GeV^6 at 1/2 central nuclear density. For purposes of comparison, we find that Π^{4q}_p(free space) $= -0.42$ GeV^6 and Π^{4q}_p(fac, in-med) $= -0.27$ GeV^6. (2) We find that the vector mass of the $\Delta(1232)$, $\delta M^u_{\Delta} = 97$ MeV. This result for the vector mass shift is about 1/4 of that found in the calculation of Ref. 3 for the nucleon at nuclear density. Without $\delta\Pi^{4q}_p$, M^*_{Δ} would be about 200 MeV higher, so it is seen that the effect of $\delta\Pi^{4q}_p$ is significant. The properties of the $\Delta(1232)$ in nuclei using QCD sum rules has also been considered recently by Jin[10] from a different point of view. We conclude that it is possible to use the experimental data on pion-nucleus scattering at the energies in the $\Delta(1232)$ region to extract a value for the four quark condensate term that enters for that resonance in nuclear matter

Two alternative approaches for extending the above analysis to consider the coupling constant $g_{\pi N\Delta}$ in free space and in the nucleus are the light-cone approach[11] and the three-point function approach,[12] respectively.

Modern facilities providing beams of electrons, photons, pions, and kaons in the GeV range will make it possible to study the higher-lying baryon resonance region. Application of the isobar-doorway analysis to these data may make it possible to determine the masses and couplings of pions to resonances above the Δ(1232). Some data exist already for pion and photon scattering in this region, and preliminary results suggest an interesting density dependence for the pion coupling to higher-lying resonances.[13] Extension of the above analysis to higher-lying resonances is therefore an interesting future direction

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